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Energy Management Strategies for Modern Electric Vehicles Using MATLAB/Simulink

Jinesh Pradip Shah, Prashant Kumar Soori, and Sibi Chacko

Abstract—The paper describes the various energy management techniques that can be implemented for a modern electric vehicle by using MATLAB/Simulink. The Renault Twizy vehicle is considered for MATLAB simulation. Regenerative braking technique is discussed, in which the kinetic energy is converted to electricity to charge the battery of the vehicle when the brakes are applied or when the vehicle is moving down the hill. A solar photovoltaic (PV) on the roof-top of the vehicle is implemented to charge the battery used in the vehicle. The simulation results are highlighted and energy management strategies are presented. The results showed that the speed control of direct current (DC) motor during the motoring mode and regenerative braking mode was successfully achieved by using a bi-directional DC-DC converter and a proportional-integral (PI) controller at various reference speeds set by the user by applying a variable load torques to the motor. The size of solar PV on roof-top of the vehicle was found to be 280 W that charged the 48 V battery of the vehicle by using a bi-directional DC-DC converter, which was evaluated by using MATLAB/Simulink.

Index Terms—Battery vehicle, DC-DC converter, DC motor, MATLAB.

1. Introduction

The major issue relating the depletion of fossil fuels, the increase in the price of oil and gas, greenhouse gas (GHG) emissions, and high environmental pollution are creating a major concern for the society and the world as well. The automotive industry is greatly attached to all the above issues. The major concern with internal combustion engine (ICE) vehicles is the continuous reduction in fossil fuels

which directly leads to the increase in the prices of petrol and gas. The other issues with ICE based vehicles are its environmental concerns of producing high percentage of greenhouse gas emissions and thus polluting the environment. The development of electric vehicles in the automotive industry can reduce these major issues to a great extent. In the recent era, most of the automotive industries have taken steps to develop green vehicles, which are clean, safe, highly efficient, and also eco-friendly. With the development of electric vehicles, battery electric vehicles (BEV), hybrid electric vehicles (HEV), and fuel cell based electric vehicles (FCEV) have the potential to replace the present conventional based vehicles (ICE based vehicles)^[1]. The current concern for the electric vehicles, which limits itself from entering the market, is due to the battery technology. The battery technology is found to be the weakest and this poor storage capability limits the battery electric vehicle range (BEV) to only specific applications, like airport stations and for small drive range applications^[1]. Some major challenges for BEV are the poor mileage, sizing and capacity constraints, dependency on power, and longer charging hours. In addition, the improvements in battery technology and public recharging installations are required^[2]. This paper describes the various charging techniques that can be implemented in an electric car in order to overcome the above constraints.

2. Methodology

The block schematics of the proposed system are shown in Fig. 1.

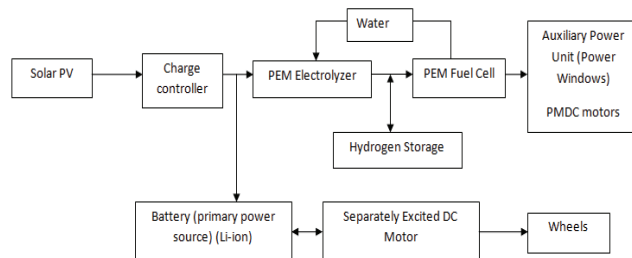


Fig. 1. Design of solar hydrogen-based fuel-cell battery-electric vehicle.

The design consists of a solar photovoltaic (PV) on the roof-top of the vehicle which is connected to a charge controller. This charge controller has a control strategy of producing hydrogen via electrolyzer and storing in the hydrogen storage tank. Unless it detects that the state of

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charge (SOC) of the battery is full, it directly starts to charge the battery until its SOC is reached to the maximum limit. The lithium ion battery and a proton exchange membrane (PEM) based electrolyzer is considered. The primary power source used here to propel the wheels of the vehicle is the battery. The design also has an additional feature of regenerative braking to charge the battery effectively during braking and down-hill motion of the vehicle. The vehicle is powered by a separately excited DC motor. Fuel cell is designed to power the auxiliary power unit. In this case a small application is considered, such as power windows which use the permanent magnet DC motor (PMDC) for its operation.

3. Vehicle Specifications

The vehicle specifications are tabulated in Table 1. Fig. 2 shows the Renault Twizy vehicle considered for simulation.



Fig. 2. Renault Twizy^[3].

Table 1: Renault Twizy specifications^[4]

Parameter	Specifications
Motor	4 kW (5 HP)
Weight	145 kg (including battery around 100 kg)
Length	2320 mm
Width	1191 mm
Height	1461 mm
Battery	48 V, 7 kWh

The vehicle also has an extendable cable for battery charging. It is capable of charging by plugging in the voltage of 220 V at 10 A (domestic electrical supply). The battery can be fully charged in three to four hours of continuous charging. The maximum torque during the vehicle's initial start provided by the motor is around 57 Nm, almost four times greater than a three wheeled scooter of 125 cm³^[4].

4. Case 1: Closed Loop Speed Control of DC Motor Using PI Controller

The closed loop speed control of the DC motor used in this paper is carried out by using a proportional-integral (PI) controller. Fig. 3 shows the control strategy used for the closed loop speed control of DC motor by using a half bridge non-isolated bi-directional DC-DC converter and a PI controller^[5].

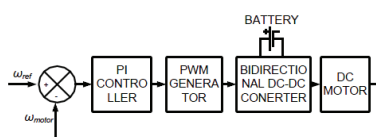


Fig. 3. Closed-loop speed control of DC motor using PI controller^[5].

In order to control the speed of the DC motor, the output voltage of the bi-directional DC-DC converter must be controlled. In order to control the output voltage of the bi-directional DC-DC converter and to bring the speed of the vehicle running at a different speed to the desired speed, a PI controller is used to provide a quick response to sudden and quick speed changes during the driving cycles. In this control strategy, the motor speed or the actual speed ω_{motor} is sensed and compared with a reference speed or the desired speed ω_{ref} as shown in Fig. 4. The error signal ($\omega_{ref} - \omega_{motor}$) is calculated and fed into the PI controller, which minimizes the error by using the proportional and integral gain values and sends the signal to the pulse width modulation (PWM) generator. The signal which is fed into the PWM generator is then compared with the high frequency saw-tooth wave equivalent to the switching frequency of the converter in order to generate pulse width modulated (PWM) control signals for the switches used in the bi-directional DC-DC converter and make the vehicle to run at the desired speed^[5].

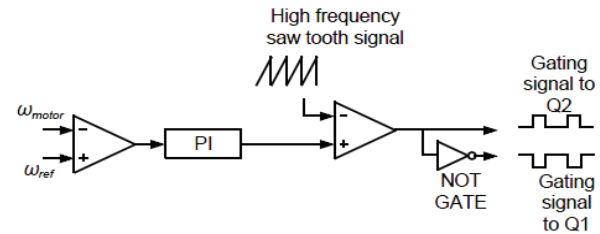


Fig. 4. Generation of gate pulses using PI controller^[5].

5. MATLAB/Simulink Model for Motoring and Regenerative Braking Mode

In this case, both motoring and regenerative braking take place in the single simulation which runs for a time period of two seconds. The speed control of the DC motor for motoring and regenerative braking is done at various reference speeds (desired speed) by applying various load torques to the motor. The concept of complementary gate switching during motoring and regenerative braking modes is used. The bi-directional DC-DC converter circuit is shown in Fig. 5.

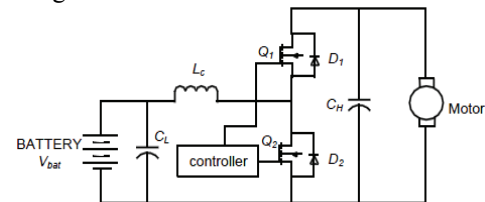


Fig. 5. Bidirectional DC-DC converter^[5].

5.1 Parameters

The below parameters are considered in MATLAB/Simulink model for running the vehicle in motoring mode:

- Motor: 5 HP, 240 V, and 1750 rpm (183 rad/s).

- Bidirectional DC-DC converter specifications:
 $L_C=1600 \mu\text{H}$,
 $C_H=470 \mu\text{F}$, $C_L=470 \mu\text{F}$
- Battery:
Voltage=48 V, battery capacity=140 Ah
- PI controller:
 $K_p=0.001$, $K_I=0.02$

5.2 Motoring Mode

The Simulink model of motoring mode is shown in Fig. 6. During the motoring mode, the desired speed of 70 rad/s is achieved, when a positive load torque of 10 Nm is

applied to the motor. It can be observed that the armature current is positive and proportional to the electrical load torque.

5.3 Regenerative Braking Mode

Fig. 7 shows that during the regenerative braking mode, the desired speed of 70 rad/s is achieved, when a negative load torque of -10 Nm is applied to the motor after a period of one second during the simulation. It can be observed that the armature current is negative and proportional to the electrical load torque.

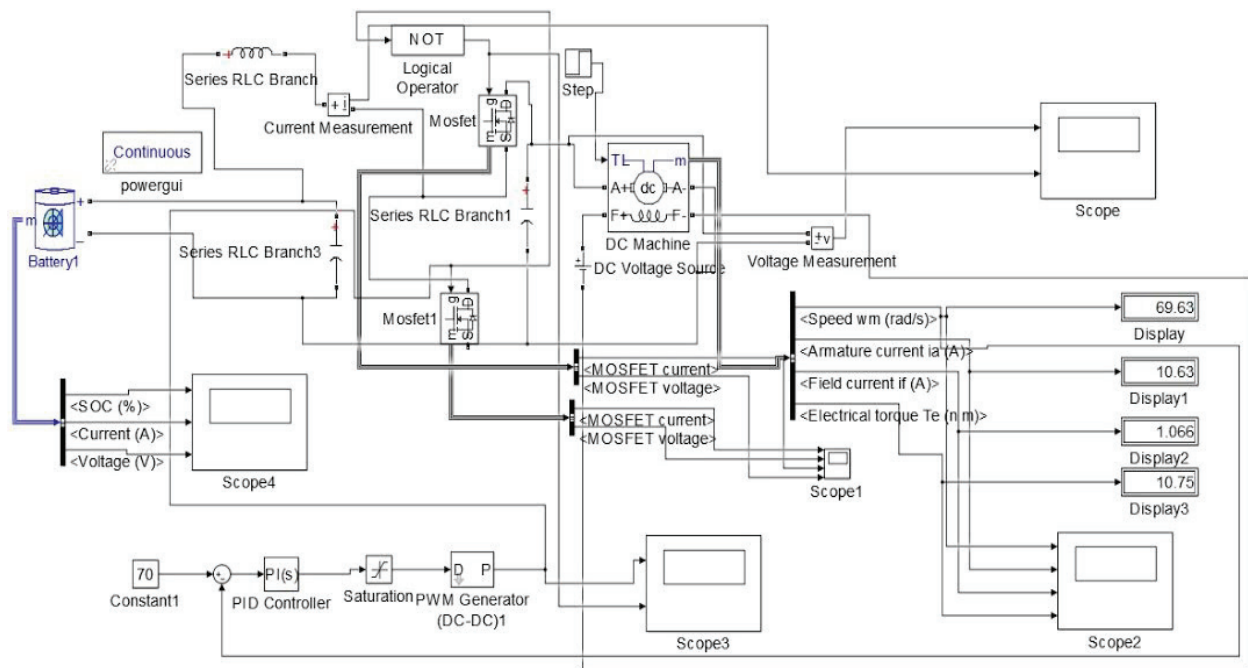


Fig. 6. MATLAB/Simulink model during motoring mode.

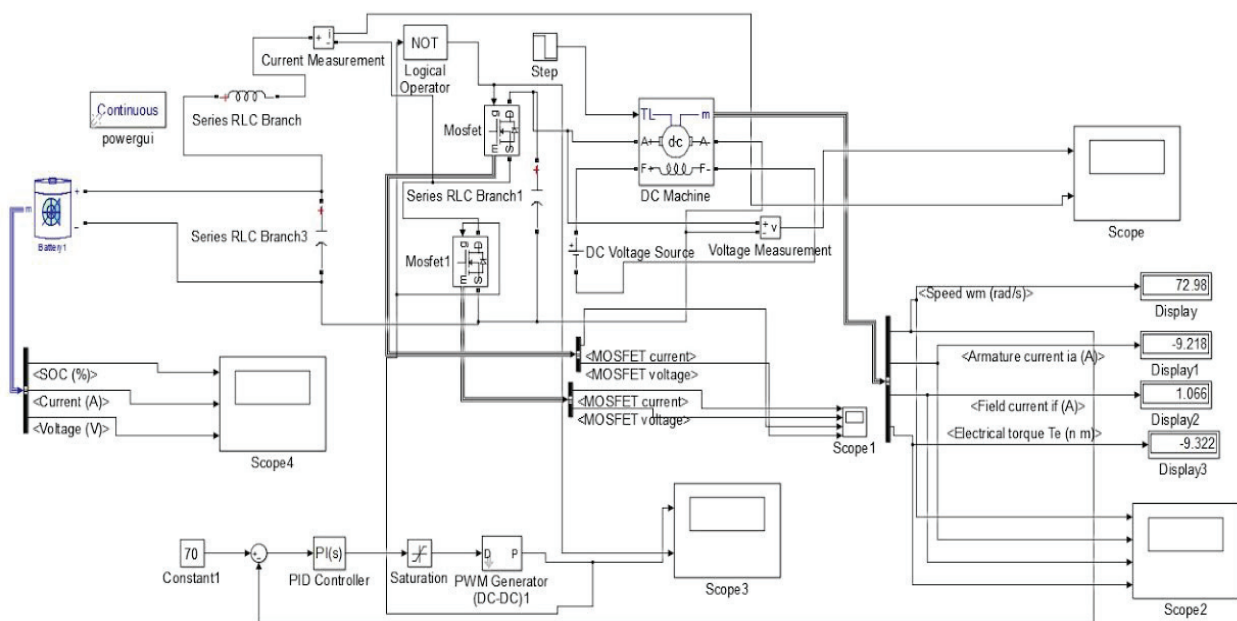


Fig. 7. MATLAB/Simulink model during regenerative braking mode.

6. Case 2: Design of Solar PV on the Roof-Top of the Vehicle

The design of solar photovoltaic (PV) for the vehicle is calculated by using the length, width, and height of the car Renault Twizy. From the dimensions of the vehicle, it is possible to calculate the area that can be covered by solar PV on the roof-top of the vehicle. The total roof-top area of Renault Twizy that can be covered is 2.76 m^2 . However, as per the vehicle dynamics, the total area cannot be utilized and hence an approximate area of 1.96 m^2 is considered for installing the solar PV on the roof-top of the car. The module selected here is a mono-crystalline silicon cell based solar PV. The module efficiency ranges between 13% and 19%^[6]. The rating of solar PV to be installed on the roof-top of the vehicle is calculated by using this efficiency and area. Assuming in mono-crystalline solar PV system, the area/Kilowatt (kW) is considered to be 7 m^2 . Sizing of solar PV is given as

$$\text{Solar PV required} = 1.96 \times 1000 / 7 = 280 \text{ Wp.} \quad (1)$$

Hence, a 280 Wp solar PV module is considered on the roof-top of Renault Twizy for charging the 48 V, 7 kWh lithium-ion battery of the vehicle.

6.1 Boost Converter Design Parameters

In the boost converter, the output voltage is

$$\text{Output voltage} = V_o = V_{in} / (1 - D). \quad (2)$$

The input voltage V_{in} is taken as 30.6 V (the maximum power point voltage of 280 Wp solar PV module exposed to 1000 W/m^2). The output voltage V_o is taken as 54 V which is the maximum charging voltage limit of the battery. So, a duty cycle (D) of 0.433 has been obtained by using (2). The switching frequency $f_s = 20 \text{ kHz}$ ^[7].

6.2 Inductor Design

The inductor for the boost converter is designed by

$$L = \frac{V_{in} (V_{out} - V_{in})}{\Delta I_L f_s V_{out}} \quad (3)$$

$$\Delta I_L = (0.2 \text{ to } 0.4) I_{OUT(max)} V_{out} / V_{in} \quad (4)$$

where ΔI_L is the inductor ripple current, $I_{OUT(max)}$ is the maximum output current necessary in the application^[8]. A factor of 0.3 is chosen to calculate the value of ΔI_L and $I_{OUT(max)}$ is taken as 70 A since the maximum charging limit of the battery is 70 A. The output voltage V_{out} is considered to be 48 V, since the battery used in the vehicle is 48 V. By substituting these values in (3), the inductance (L) is found to be $1.68 \times 10^{-5} \text{ H}$.

6.3 Capacitor Design

The capacitance value is calculated using (5):

$$C_{out} = I_{OUT(max)} \times D / (f_s \times \Delta V_{out}) \quad (5)$$

where ΔV_{out} is typically 0 to 10% of output voltage.

In this design, ΔV_{out} is assumed to be 5% of the output voltage and its value is found to be 2.4 V. The capacitance is found to be $C = C_{out} = 6.31 \times 10^{-4} \text{ F}$.

The above inductor, capacitor, and duty cycle values obtained are used for the boost converter (charge controller) for safe battery charging by using solar PV^[9].

7. MATLAB/Simulink Model of Solar PV—Battery Charging Using Boost Converter

Fig. 8 describes the Simulink model of solar PV to charge the battery by using the boost converter at a constant voltage of 48 V and also within the battery charging current of 70 A for the safe battery charging when a solar irradiance of 1000 W/m^2 is applied on the 60 cells module rated 280 Wp.

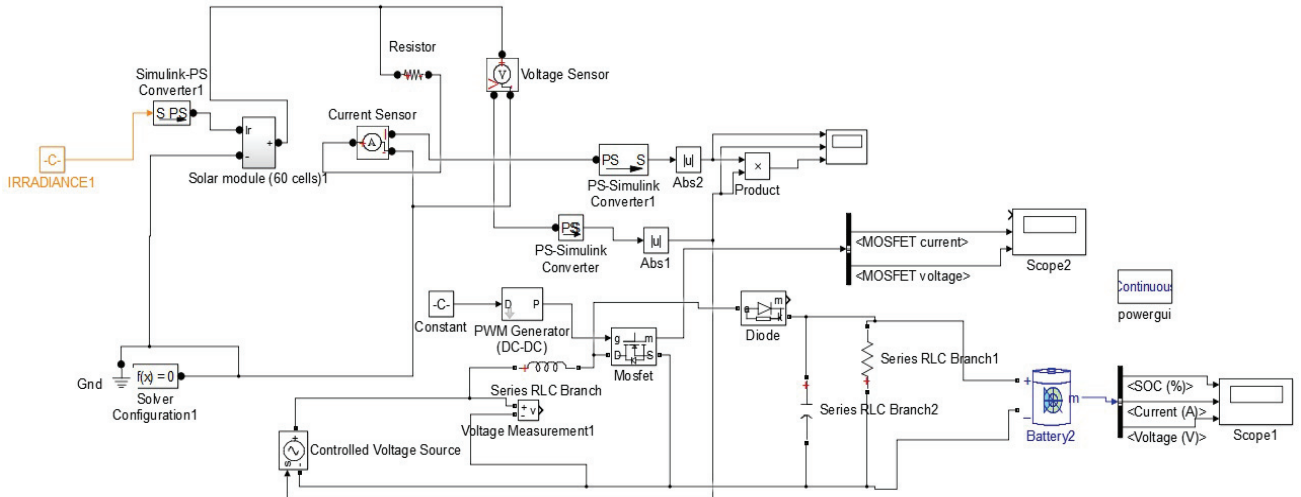


Fig. 8. MATLAB/Simulink model of solar PV to charge the battery by using boost converter.

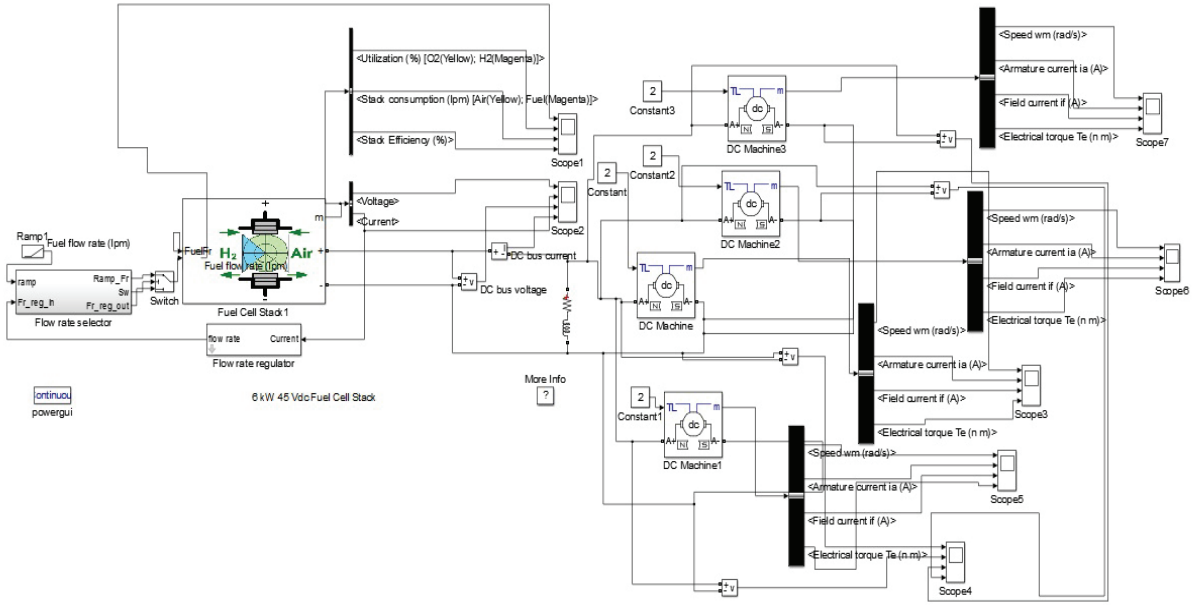


Fig. 9. MATLAB/Simulink model of fuel cell powered PMDC motors used in windows.

A controlled voltage source is used in the above Simulink model in order to feed the output voltage from solar PV to the boost converter circuit. The parameters used for the boost converter are the inductance $L = 1.68 \times 10^{-5} \text{ H}$, capacitance $C = 6.31 \times 10^{-4} \text{ F}$, resistor $R = 200 \Omega$, duty cycle $D = 0.43$. The model is simulated for a simulation time of one second and the results are obtained.

8. Proton Exchange Membrane (PEM) Based Fuel Cell for Powering Auxiliary Loads

The fuel cell considered here is of smaller rating compared with the one usually used in the fuel cell based hybrid electric vehicle. The main use of the fuel cell designed for this vehicle is to provide power to the auxiliary applications used in a vehicle. The overall power consumption of auxiliary loads is around 4.3 kW. The MATLAB/Simulink model of the fuel cell powered permanent magnet direct current (PMDC) motors for the power windows application is shown in Fig. 9.

The above Simulink model presented in Fig. 9 shows how the fuel cell stacks is connected to the four PMDC motors of the power windows. It is clear that the fuel flow rate of the fuel cell stack is controlled by using a fuel flow regulator. The above block also shows that the four PMDC motors of the power windows are run by applying a load torque of 2 Nm at a 12 V DC system voltage.

9. Results and Discussions

9.1 Motoring Mode

In the motoring mode, the duty cycle of the switches for a bi-directional DC-DC converter (as shown in Fig. 5) fed separately excited DC motor is calculated as

$$\frac{V_2}{V_{\text{batt}}} = \frac{1}{1 - D_{Q1}} \text{ or } \frac{V_{\text{batt}}}{V_2} = D_{Q2} \quad (6)$$

$$D_{Q1} = 1 - D_{Q2} \quad (7)$$

where D_{Q1} and D_{Q2} are the duty cycles of switches Q1 and Q2, respectively; V_{batt} is the battery voltage.

In Case 1, a positive load torque of 10 Nm is applied to the motor till a time period of one second and then the negative load torque is applied for another one second. The armature voltage V_2 is around 98 V which can be observed in Fig. 10. The battery used here is 48 V, 140 Ah. The duty cycle of gates Q1 and Q2 are calculated by using (6) and (7), respectively. Its value is found to be $D_{Q2} = 0.49$ and $D_{Q1} = 0.51$.

It is seen that the complementary gate switching takes place as in the motoring mode $D_{Q1} > 0.4$ and $D_{Q2} < 0.6$. Hence the bi-directional DC-DC converter is acting in a boost mode, which propels the DC motor of the vehicle to run at the desired speed of 70 rad/s.

From Fig. 10, it is clear that an armature voltage around 98 V is achieved for the motor running at a speed of 70 rad/s with a load torque of 10 Nm. The inductor current is around 21 A which is positive in the case of the motoring mode.

Fig. 11 shows the battery state of charge (SOC), battery current, and battery voltage. The state of charge of the battery is seen to decrease, as in the motoring mode the battery starts discharging. It is clear from Fig. 11 that the battery current is positive, since the current is drawn from the battery to power the motor. The discharging current is in the range of 20 A to 30 A for running the vehicle at 70 rad/s. The battery voltage is around 48 V as the maximum battery voltage limit is 54 V.

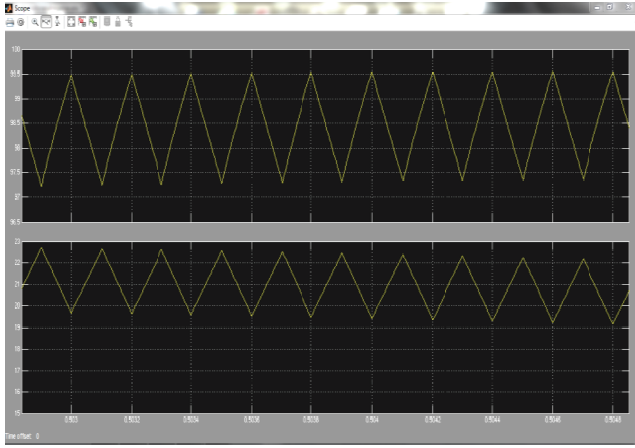


Fig. 10. Armature voltage and inductor current.

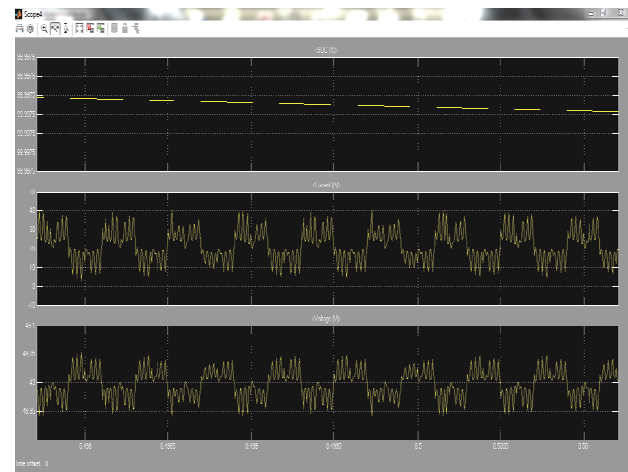


Fig. 11. Battery SOC, voltage, and current.

9.2 Regenerative Mode

In the regenerative mode, the duty cycle of the switches for a bi-directional DC-DC converter fed separately excited DC motor is obtained by using (8) and (9), respectively.

$$\frac{V_2}{V_{\text{batt}}} = \frac{1}{1 - D_{Q1}} \quad \text{or} \quad \frac{V_{\text{batt}}}{V_2} = D_{Q2} \quad (8)$$

$$D_{Q1} = 1 - D_{Q2}. \quad (9)$$

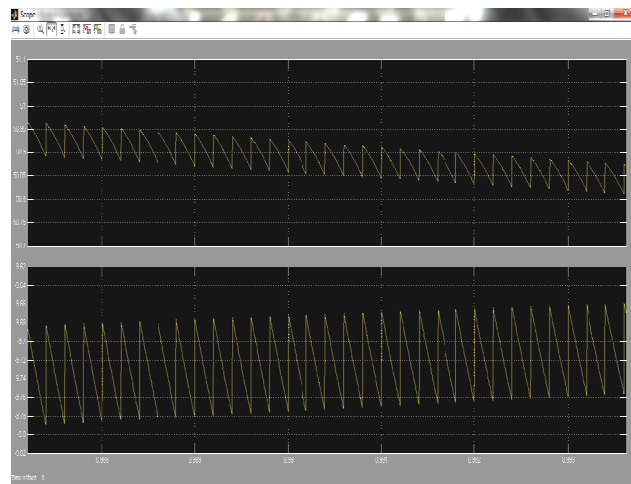


Fig. 12. Armature voltage and inductor current.

In the second case, a negative load torque of -10 Nm is applied to the motor after a time period of one second. The battery rating is 48 V , 140 Ah . The armature voltage V_2 is around 50.9 V which can be observed in Fig. 12. Duty cycle of $Q2$ (D_{Q2}) is found to be 0.94 and that of $Q1$ (D_{Q1}) is 0.06 .

From Fig. 12 it is clear that the armature voltage of 50 V is achieved for the motor running at a speed of 70 rad/s with a load torque of -10 Nm . Thus the voltage from 98 V comes down to 50 V (nearing the battery voltage) to charge the battery during this mode. The inductor current is around -10 A which is negative in the case of the regenerative braking mode. Thus the motor voltage is stepped down by the bi-directional DC-DC converter to the battery voltage and the current flow is reversed during this mode.

Fig. 13 represents the battery state of charge (SOC), battery current, and battery voltage. The state of charge of the battery is seen to be increasing, as in the regenerative mode the battery starts charging. It is clear from Fig. 13 that the battery current is negative, since the current flows in the reverse direction. The charging current is in the range of 20 A to 30 A for running the vehicle at 70 rad/s , which is well within the charging limit of the battery. The battery voltage is found to be around 48 V as the maximum battery voltage limit is 54 V .

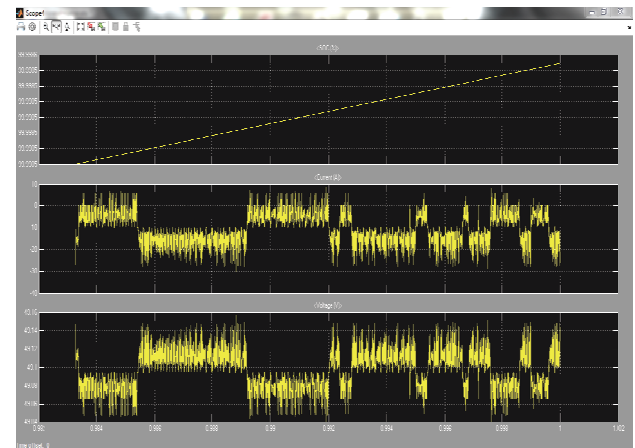


Fig. 13. Battery SOC, voltage, and current.


 Fig. 14. Maximum power point current, voltage, and power for 280 Wp module at solar irradiance of 1000 W/m^2 .

9.3 Solar PV to Battery Charging

Fig. 14 shows that the solar PV output for a 280 Wp solar PV exposed to a solar irradiance of 1000 W/m² produces the maximum power P_{\max} of 268 W with a maximum power point voltage V_{mpp} of 30.6 V and maximum power point current I_{mpp} of 8.7 A.

The maximum power point voltage V_{mpp} of 30.6 V is fed to the boost converter to step up the voltage from 30.6 V to a constant voltage of 48 V at a charging current of –60 A, which is within the charging limit of the battery. From Fig. 15, it is clear that the battery state of charge (SOC) increases as the battery starts charging using the solar PV.

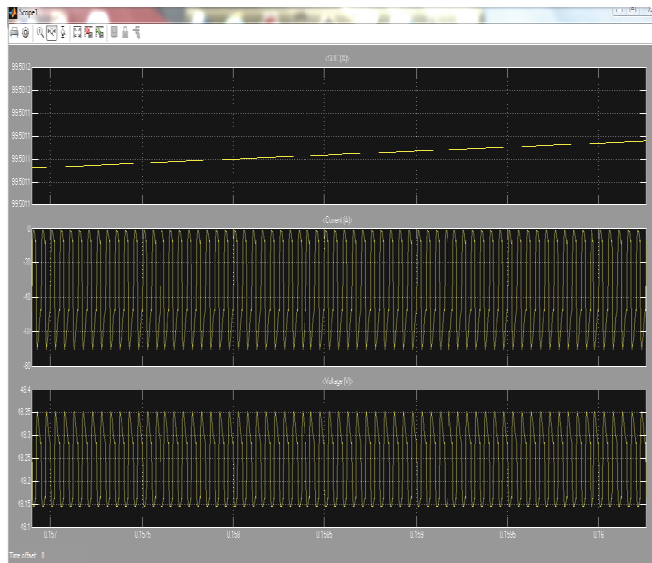


Fig. 15. Battery SOC, voltage, and current.

9.4 PEM Fuel Cells to Power Windows

Fig. 16 shows the fuel cell voltage and fuel cell current, which is around 12 V and 8.3 A. So it produces around 100 W of power at standard operating conditions and powers the 4 PMDC motors of the power window used in the electric vehicle.

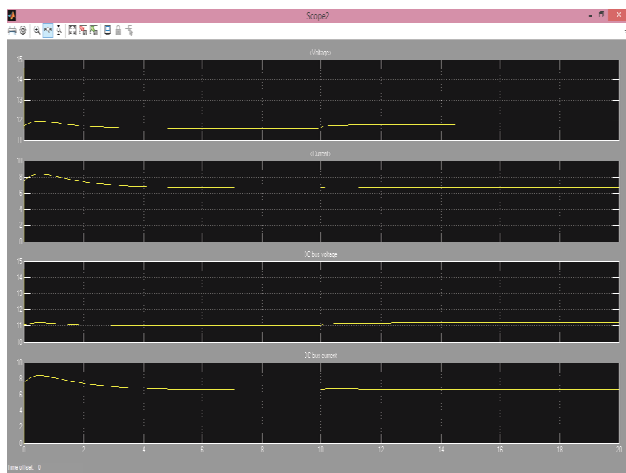


Fig. 16. Fuel cell voltage and current.

10. Conclusions

This paper presents various energy management techniques that can be implemented for the electric vehicle application. The performance of the system has been verified by simulating with the MATLAB/Simulink environment. It is found that the use of regenerative braking technique leads to energy saving in vehicles and the idea of using solar PV on roof-top of the vehicle leads to further energy saving making the pure electric vehicle more energy-efficient and improving the range of the vehicle.

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Prashant Kumar Soori's and Sibi Chacko's photographs and biographies are not available at the time of publication.